FLIGHT TEST OF A TECHNOLOGY TRANSPARENT LIGHT CONCENTRATING PANEL ON SMEX/WIRE

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Abstract

A flight experiment has demonstrated a modular solar concentrator that can be used as a direct substitute replacement for planar photovoltaic panels in spacecraft solar arrays. The Light Concentrating Panel (LCP) uses an orthogrid arrangement of composite mirror strips to form an array of rectangular mirror troughs that reflect light onto standard, high-efficiency solar cells at a concentration ratio of approximately 3:1. The panel area, mass, thickness, and pointing tolerance has been shown to be similar to a planar array using the same cells. Concentration reduces the panel's cell area by 2/3, which significantly reduces the cost of the panel. An opportunity for a flight experiment module arose on NASA's Small Explorer / Wide-Field Infrared Explorer (SMEX/WIRE) spacecraft, which uses modular solar panel modules integrated into a solar panel frame structure. The design and analysis that supported implementation of the LCP as a flight experiment module is described. Easy integration into the existing SMEX•LITE wing demonstrated the benefits of technology transparency. Flight data shows the stability of the LCP module after nearly one year in Low Earth Orbit.

Background

Solar concentrating photovoltaic arrays have been developed over the last twenty years to a state of flight readiness. The main impetus for their development has been to decrease the cost of prime power generation, in terms of $/Watt, by replacing expensive high efficiency space-quality solar cells with less expensive optics. The optics effectively replace solar cell area by collecting insolation (sunlight) and directing it to the now smaller cell areas. Another potential advantage of solar concentrators is the ability to more effectively shield the solar cells against hazardous environments, while maintaining the low mass needed for space solar arrays.

Although several flight experiments have flown both reflective (mirror) and refractive (lens) concentrating panels, the first concentrating arrays to fly as prime power for space missions have only appeared in the last three years. The first flight of a concentrator array for prime power occurred with Deep Space 1 using the SCARLET modular fresnel lens technology.[1] More recently, the LCP technology flew as part of the prime power system for the SMEX mission described in this paper.[2] A third concentrator configuration using large reflector panels has also flown on a large communications spacecraft.[3]

A perception of increased risk to mission success has been a factor preventing even more widespread use of concentrator technology. The primary areas of concern are associated with degradation of optics, thermal control of the solar cell under increased and possibly uneven illumination, and the need to more accurately point the arrays towards the sun. Optical degradation is a particularly difficult risk to manage because the sources of contamination products and their environmental interactions are difficult to predict, model, and test on the ground.

LCP Design

Technology Transparency Objective

A major objective of the Light Concentrating Panel (LCP) development was to retire the perceived risks of a solar concentrator panel by using the concept of "technology transparency." In this approach, the product being developed is modeled on an existing design with the goal of achieving the same or better performance at lower cost, without significant changes in form, fit, or function.

For a solar panel, we identified those features and characteristics that typically are key inputs to the system engineering of a solar array. The characteristics of a planar panel that we wanted to emulate include specific mass (Watts/kilogram), specific area density (Watts/m^2), packaged panel efficiency (Watts/m^3 which reduces to panel thickness for an equivalent area density), power profile over time (orbital environment degradation), and panel pointing tolerance. In addition, we wanted to achieve a similar manufacturability using existing cell and panel technology, and provide familiar interfaces to the array hold-down and deployment mechanisms.

Panel and Element Design

The LCP design that addressed these technology transparency objectives is shown in Figure 1. It is a panel of similar thickness to large planar panels (about 2.5cm), comprising an array of concentrator elements. Each element consists of a four-sided mirror trough with each wall having a high solar reflectance, and a solar cell positioned at the bottom aperture. The mirror trough and cell are mounted upon a base plate consisting of a sheet of material having high thermal conductivity. The solar cells interconnect to a flex-circuit wiring layer which is integral to the base plate using conventional interconnect derived from electronic packaging technology.

Although the mirror trough walls and base plate can be considered individually as components of each element, in the construction of multi-element panel, these components span multiple elements. Using longer egg-crated (interleaved) mirror strips and a large multi-element base plate allows fewer piece-parts and provides an integral structural design which helps the panel overall performance, by minimizing the need for added structure in larger panels. Both mirrors and base plate are fabricated from thin sheets of graphite fiber reinforced composite (GFRC) material for achieving high stiffness and lightweight in its structural function.

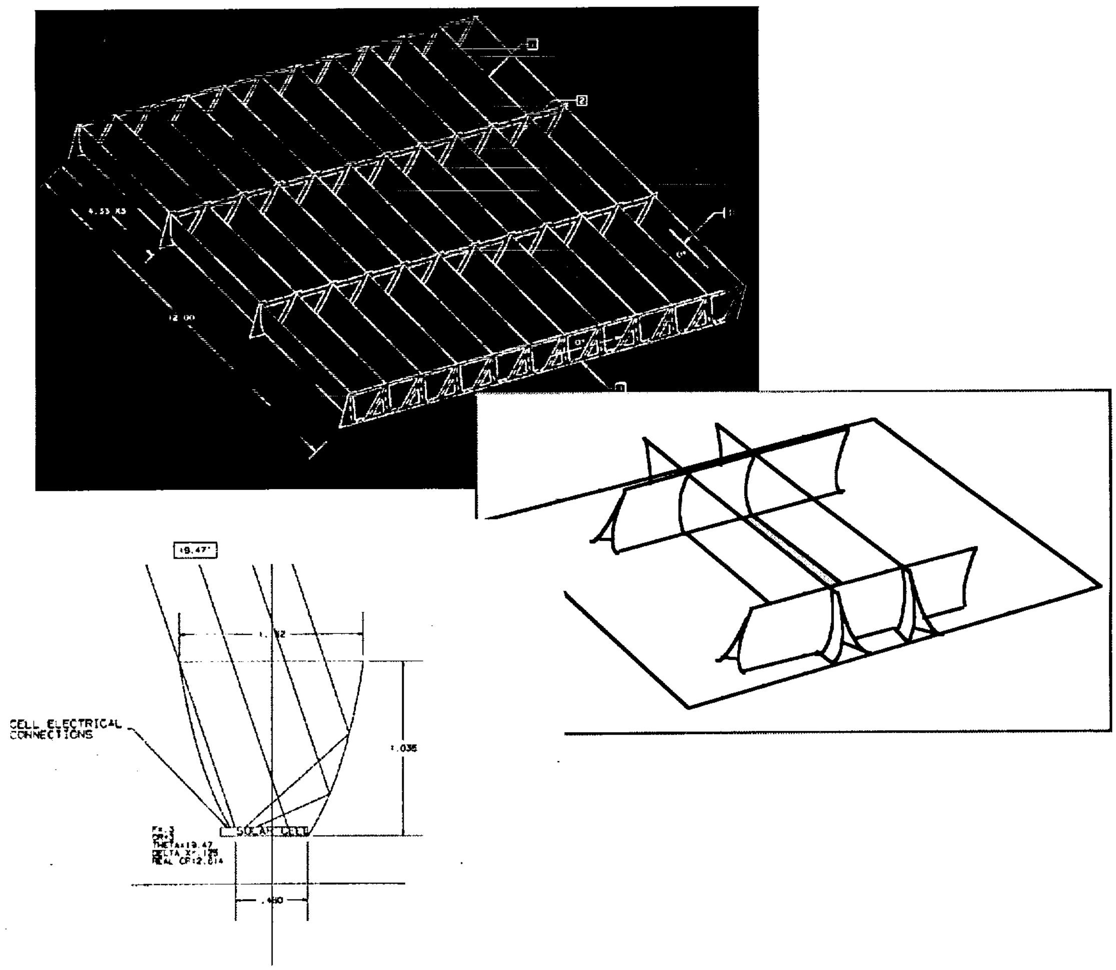

Figure 1. Conceptual Design of the Light Concentrating Panel

The theory of operation of the LCP is basic and analogous to planar arrays. Within each concentrator element, incoming sunlight is directed to the solar cells both by direct illumination, and by reflection off the trough mirror walls (see Figure 2). For most of the mirror, a single reflection suffices to place the ray of sunlight onto the solar cell, whenever the element is pointed toward the sun within the required acceptance angle. The acceptance angle is defined by the maximum angle that the panel can be pointed off of normal to the sun before reflected rays begin to miss, or "walk off," the solar cell. The ray-tracing example in Figure 1 illustrates this, showing the incoming sunlight arriving at near the maximum acceptance angle for that design, about 20 degrees off normal; further off-pointing would cause reflected rays to walk off the left side of the solar cell.

Reflected light incurs a small power loss due to mirror spectral absorptance and non-specularity (scatter). Only in the small corners of the trough are two or more reflections often incurred prior to reaching the cell. Light reaching the cell assembly passes through a transparent coverglass and is converted to electricity by the photovoltaic cell. Thermal control of the cell is accomplished by radiating directly off the cell front surface, and by conduction through the cell to the base plate for radiation across the entire back surface. Since the best mirrors are poor emitters, the mirrors themselves do not contribute significantly to the thermal control of the element.

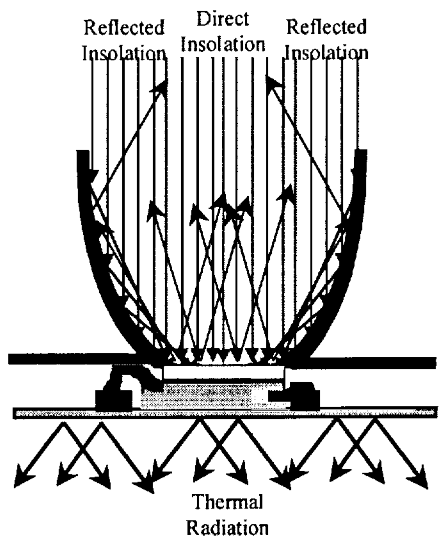

Figure 2. Basic LCP Element Operation

Elements can be treated electrically as individual solar cells, and are connected in series parallel relationships to achieve appropriate panel voltage and current. The main difference in interconnecting elements, as opposed to solar cells in a conventional planar array, is that there is a significant spacing between the cells. This provides a benefit compared to planar arrays that must pack the solar cells as tightly as possible to maximize light collection. The LCP elements hide these inter-cell areas underneath useful mirror area making assembly and repair of individual cells considerably easier. The assembly approach uses surface mounted solar cells and thermosonic wire bonds to create a cell array that is similar in technology to today's large flex-circuit assemblies, which enables implementation of automated bonding and assembly equipment used in those kinds of applications. The cell spacing that enables this is shown in the photograph of Figure 3, depicting a cell array prior to application of the mirror.

Figure 3. Cell Array Prior to Application of Optics

Panels comprising arrays of these elements in a fixed configuration can be accordion folded and deployed in the same manner as planar panels, and use the same kinds of panel and array auxiliary hardware as do conventional planar panels, including array harness, blocking diodes, inter-panel hinges and linkages and tie-downs. As with a planar panel blank "keep-out" areas can be implemented for interface hardware.

We have shown[2] the performance of the generic design of the LCP concentrator to be similar, in terms of Watts/kilogram and Watts/m^2, to a rigid planar panel using the same type of solar cell. This analysis has shown that, at a baseline concentration ratio of 3:1, the pointing tolerance of the LCP in the most sensitive axis is +/-20 degrees. The pointing tolerance was confirmed using a representative ground test model. Thermal analysis has shown that the panel reaches a peak temperature on orbit that is about 20C higher than an equivalent planar rigid panel. [3]. Table 1 summarizes the results of these prior studies.

Table 1. Comparison of concentrator and planar performance and cost

Panel Type	Structure Specific Mass (kg/m^2)	Photovoltaics Specific Mass (kg/m^2)	Cell Temp (degC)	Area Specific Power (W/m^2)	Mass Specific Power (W/kg)	Typical Panel Costs ($/Watt) In Quantity
Planar GaAs	1.25	1.48	50	228	84	$450
LCP GaAs	1.80	0.53	70	224	95	$250
LCP MBG	1.80	0.53	70	279	120	$280

SMEX/WIRE Flight Test Panel

A flight model of the solar concentrator was fabricated, tested, and flown as part of the SMEX/WIRE primary power system. SMEX/WIRE was an astronomy mission that used advanced composite designs for the bus structure and the solar panels. One of the advanced technologies demonstrated on WIRE was the SMEX•LITE solar panel, which uses modular solar panel modules, each ~(21cm x 44cm), mounted onto a composite window-frame. In the approach, solar array substrates of a standard physical and electrical configuration are pre-populated with high efficiency cells and mounted onto a composite frame designed for a specific mission. For this mission, two wings with nine modules each were used. NASA allocated one module on each wing for advanced technology, allowing an LCP module to substitute for one of the standard planar modules in one wing. The LCP flight panel was designed based on SMEX•LITE module requirements, which are summarized in Table 2. Compliance to requirements was demonstrated for each item through analysis, inspection or test.

Table 2. SMEX•LITE requirements used in the design of the LCP panel for WIRE

Item	Requirement	Verification
Physical	Dimensions of 43.61cm X 20.93 cm	Inspection
Power Output	35 Volts Vmp and 17W at maximum operating temperature	Test / Analysis
Voltage Tap	Located so that Voc of the upper string <26.3V @ -80°C	Analysis
Bypass Diode Protection	Bypass diodes to be provided for each cell assembly	Inspection
Blocking Diode Protection	Redundant blocking diodes for both taps	Inspection
Isolation	100MegOhms between cell circuit and structure	Test
Contamination / Outgassing	<1% Total Mass Loss; <0.1% Volatile Condensable Material	Analysis / Heritage
Mass	<0.27kg not including substrate	Design / Test
Environmental Durability	Accidental Damage / Malfunction, Panel Outgassing, Vibration/ Acoustic, Thermal cycling, Ultraviolet Radiation, Charged Particle Radiation, Atomic Oxygen, Micrometeoroid / Space Debris, Shadowing	Heritage / Analysis (Thermal cycling & vibration durability verified by test)

The LCP module electrical design, which connects individual SAC elements in series to meet voltage requirements, and provided an appropriate voltage tap point, is shown in Figure 4. The Printed Wiring Board (PWB), or flex circuit implementation, used to connect the various mounted solar cell assemblies according to the schematic of the electrical design, is shown in Figure 5, and includes the wiring traces providing the required voltage tap, and feed-through of the flex-circuit to the panel backside. A sketch of the solar cell configuration within an element is shown in Figure 6.

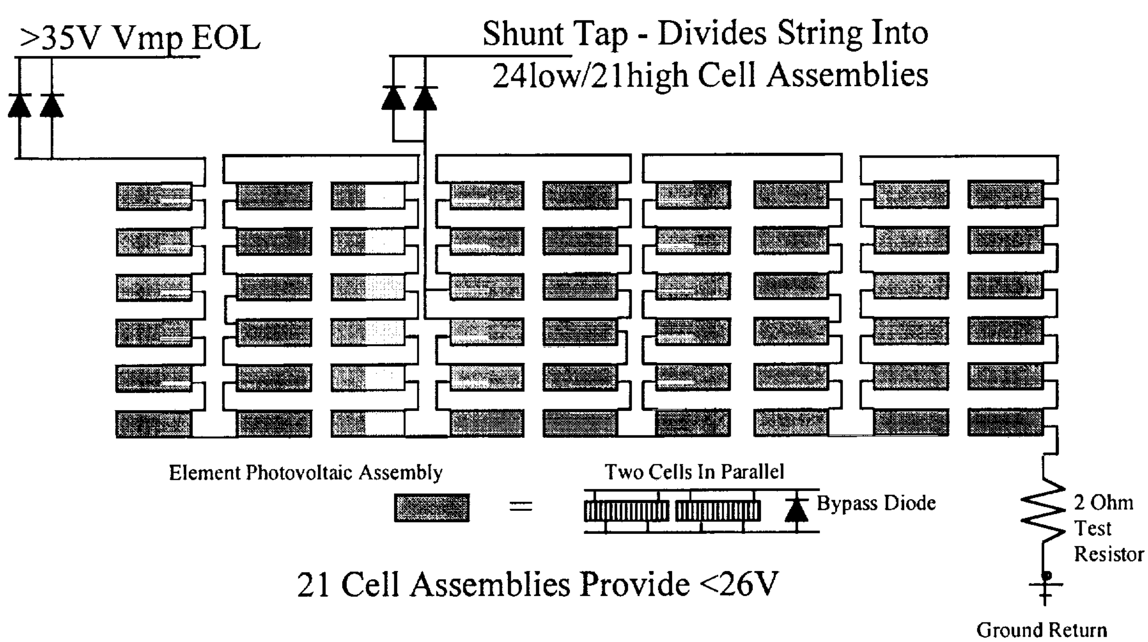

Figure 4. Solar Array Concentrator electrical schematic

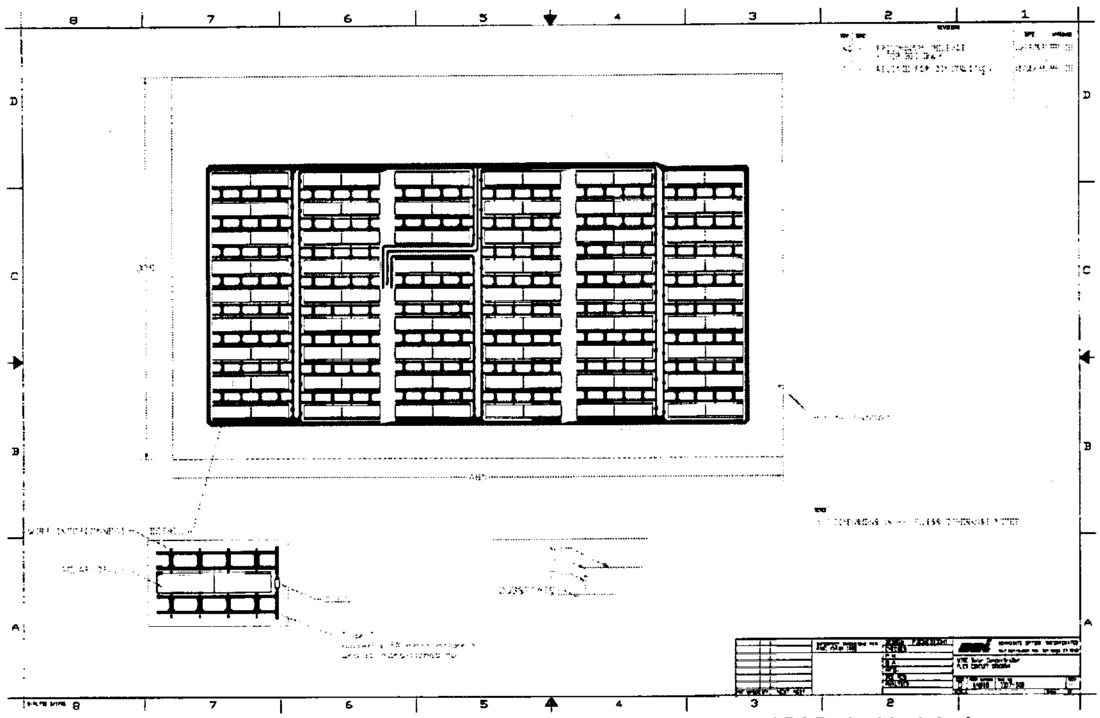

Figure 5. Printed Wiring Board (flex circuit) implementation of SAC electrical design

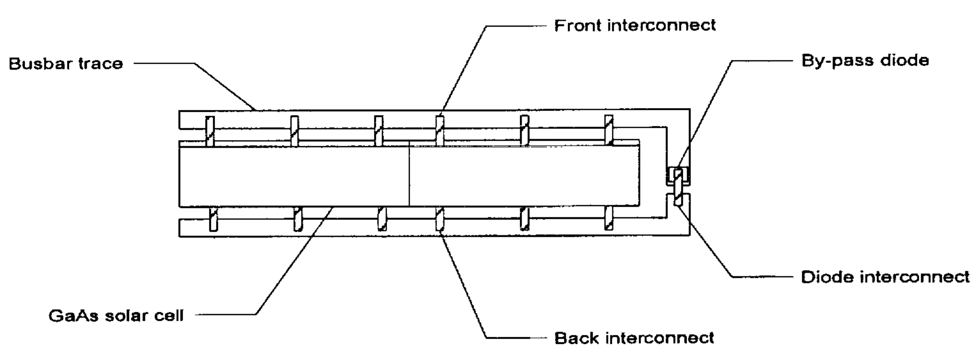

Figure 6. Solar Cell Assembly design.

SMEX/WIRE LCP Module Design Analysis

Structural, Thermal and Electrical/Photovoltaic analysis was performed on the specific LCP module design to assure that it would meet requirements. The LCP module's structural durability was analyzed by creating a Finite Element Model (FEM) of the structural components of the design, adding in the non-structural mass (NSM), constraining the model to represent the launch and operating conditions and determining the stresses imposed on the various structural elements. The results of the maximum principal stresses, shear stresses and buckling loads indicated a minimum margin of safety of greater than 2 for all components of the design, indicating a robust structural response.

Two thermal models were generated with applicability to this program to determine the operating temperatures of the solar cell and other components in space. A detailed or micro-model of the LCP element, was used to determine the detailed temperatures of the components in a steady state and orbital varying thermal environment. The micro-model assumed the SAC was not influenced by the supporting array structure, and so could use the repeatability of the design to allow increased model resolution. A second, less detailed or macro-model was developed specifically for this effort and used to determine the effect of the connection between the LCP module and the supporting solar array frame. Both models were used as inputs to the electrical analysis, and also reviewed to determine if maximum allowable temperatures for the components might be exceeded and to determine if differential temperature induced stress from Coefficients of Thermal Expansion could potentially be a problem.

The micro thermal model nodal model is shown in Figure 7. The model was run for the maximum case environment with worst case end-of-life material thermal properties listed in Table 3, in order to evaluate the worst-case temperature conditions. The result of the micro-thermal model under these conditions is shown in Figure 8. The peak solar cell temperature is 103C, and the temperature gradients throughout the concentrator element, i.e. from cell to radiator to mirror, are relatively small, in the range of 3C. Since the chosen orbit for SMEX/WIRE is sun-synchronous, we expected the earth load on the concentrator to be small, and therefore the peak temperature to more resemble that seen in this model in the time near eclipse entrance, or about 85C.

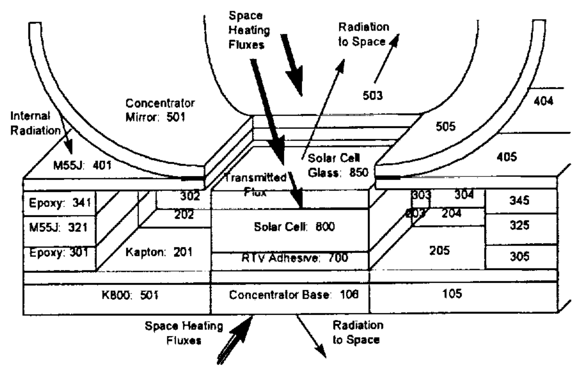

Figure 7. Micro-thermal model nodal arrangement.

Table 3. Micro thermal model worst case, end-of-life material properties and environments.

Property/Environment	Value
Solar Cell Absorptance	0.85
Solar Cell Efficiency	0.15
Mirror Absorptance	0.15
SAC Backside Absorptance	0.39
Solar Flux	1393 W/m2
Earth IR	236 W/m2
Earth Albedo	42% of Solar

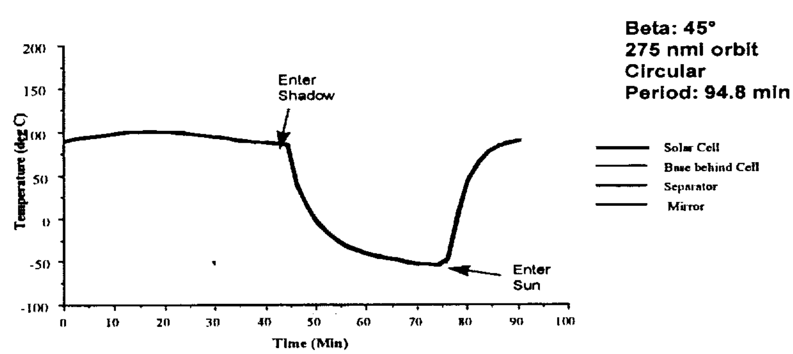

Figure 8. Results of the micro-thermal model.

Using the micro-thermal model results as a baseline, we then determined the effects of mounting the concentrator on the SMEX•LITE frame using the macro thermal model. The analysis was used to determine temperature gradients from one element to the next based on blockage of radiating elements and the conduction of waste heat into the frame structure. The magnitude of this thermal gradient was 5C and results in an estimation of peak solar cell temperature increasing to 108C. This peak solar cell temperature was then used in the electrical analysis for sizing the solar cell strings.

The electrical analysis was based on a preliminary electrical design, which arranged the cells in series parallel relationships and created the physical layout compatible with the concentrator element apertures. The solar cell string electrical design, as shown in the schematic in Figure 3, used sufficient cells in series so as to exceed the minimum end-of-life (EOL) voltage of 35 volts. In addition, a low temperature analysis at -80°C was used to determine the appropriate placement of the voltage tap within the solar cell string. The schematic was implemented in a flex circuit configuration that accounts for the placement of the cells within the substrate assembly, the potential approaches for bussing the current and the amount of metallization required to maintain a low series resistance loss.

The electrical analysis was divided up into a beginning-of-life (BOL) analysis to determine the voltage and current of the design at peak temperature, and an end-of-life (EOL) analysis to evaluate the effects of contamination, space radiation, micrometeoroids and thermal cycling that can degrade the output of the solar cell strings. The BOL analysis is summarized in the power chain analysis shown in Table 4. The EOL degradation factors are broken up into their effects on voltage and current, separately and summarized in Table 5. Finally, an analysis of the low temperature operation of the solar cells has shown that the tap voltage at -80°C is less than 26 volts, less than the maximum tap voltage requirement of 26.3V.

Table 4. Beginning of life analysis of LCP module electrical outputs.

Item	Efficiency	W/m^2
Insolation	—	1350
Optical Efficiency	0.95	1283
18%GaAs @100°C	0.15	192
Wiring Efficiency	0.99	190
Mismatch Loss	0.99	188
Net Efficiency	0.14	188
	Power for 0.091m° =	17.2 W

Table 5. End of life analysis of LCP module outputs considering environmental degradation factors.

Item	Vmp	Imp	Pmp
BOL Outputs	38.7V	0.444A	17.2W
Optical Degradation		0.95	
Coverslip Darkening		0.985	
Radiation Degradation	0.99	0.99	
Series Resistance Increase	0.98		
(From Thermal Cycling)			
EOL Outputs	37.5V	0.411A	15.4W
Output After Resistor	36.7V	0.411A	15.1W

SMEX/WIRE Power System Design

WIRE employs a direct energy transfer (DET) power system that maintains a bus voltage between 22 and 34 volts. A partial linear sequential shunt regulates the solar array output. The solar array and battery are sized to support a load of 182 watts at end of life. The mission design life is 4 months in a full-sun, sun-synchronous orbit with a perigee altitude of 470 km and an apogee altitude of 540 km.[4]

Solar Array Module Electrical Configuration

The WIRE solar array consists of two wings with 9 solar cell module modules on each wing. The baseline SMEX•Lite solar array modules each consist of one string of 50 GaAs/Ge solar cells in series. The cell size is 4 x 4 cm. The module direction alternates to minimize stray magnetic fields. Figure 9 is a diagram of the WIRE solar array electrical configuration. The LCP module is wired in parallel with the baseline module modules. Each module is tapped to allow shunting of current, and contains parallel-redundant blocking diodes.

The electrical configuration of the LCP module, shown in Figure 3, presents the same electrical interfaces to the power system as for the planar modules. Current from the LCP module is measured by taking the voltage across a 2Ω resistor in series with the solar cell strings on the return side of the module. The LCP current thus measured is at the bus voltage less the voltage drop across the resistor. The solar array is sized for a voltage at peak power of 34 volts at end of life at the maximum predicted array temperature. In sunlight the bus voltage is approximately 31 volts, depending on the voltage-temperature limit selected for the battery. When the LCP module is not shunted, the measured current will be slightly on the short-circuit-current side of the knee of the module current-voltage curve. When the LCP is shunted, it will operate closer to short-circuit current. The 2Ω resistor is on the return side of the module so that total module current can be measured whether or not the module is shunted. There are two temperature sensors on each WIRE solar array wing. One temperature sensor is on the back side of the LCP.

Telemetry System Design

For communications, WIRE uses an S-band transponder that interfaces directly with the spacecraft computer system (SCS). The SCS has an 80386 processor with a 387 coprocessor that host the command and data handling (C&DH) software. The spacecraft controls all data flow using a MIL-STD-1553 data bus.[5] Power system telemetry, including solar array currents and temperatures, is conditioned in the Spacecraft Power Electronics (SPE) unit.

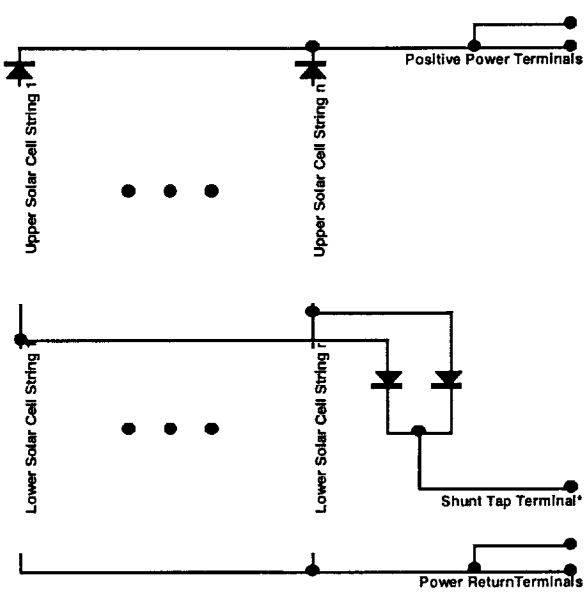

Figure 9. WIRE Solar Array Electrical Configuration.

SMEX/WIRE Concentrator Module Integration & Verification

The as-built configuration of the LCP module is shown in Figure 10. Figure 11 shows how the LCP module integrated into the SMEX•LITE panel. It is noteworthy that no special modifications to the modular panel were needed to incorporate the LCP module – this was a natural fallout of the technology transparency of the design.

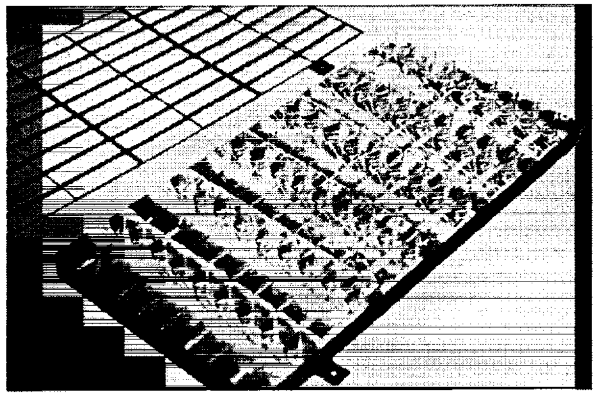

Figure 10. LCP Implemented as a SMEX•LITE Module

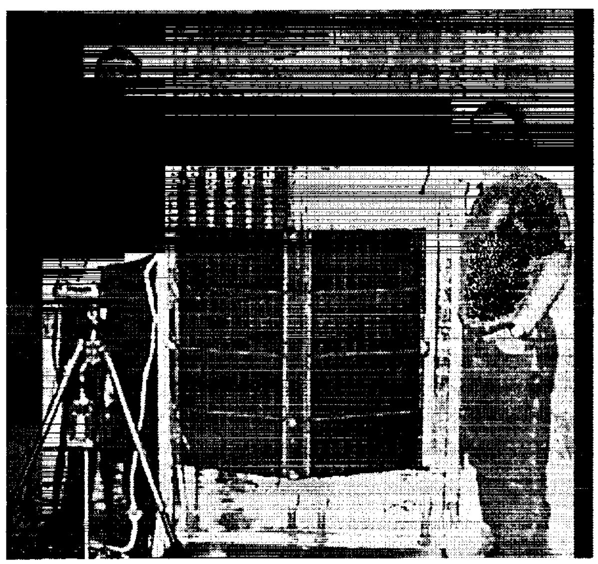

Figure 11. LCP Module Integrated into SMEX•LITE Wing

After integration of the LCP module into the wing, NASA performed ground testing including solar simulator illumination of the panel. The results of the solar simulation test are shown in Figure 12. Because the LCP module was an integral part of the array circuit, it could not be tested separately. To determine its performance, the panel was tested twice – once fully illuminated and a second time with the concentrator module covered with black cloth. The results show the extra current provided by the LCP as expected. The small bump in voltage seen in the lower right hand corner of the I-V curve is indicative of additional cells placed in series to accommodate the higher on-orbit operating temperatures, which cause greater voltage degradation.

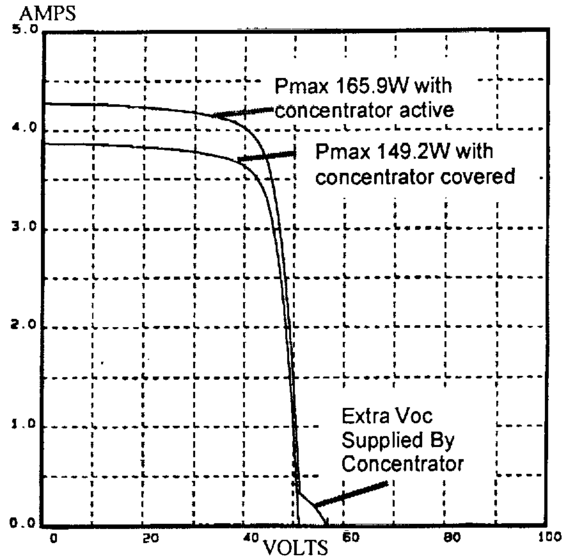

Figure 12. Ground Test Results Using NASA's Solar Simulator

Evaluation and Interpretation of Telemetry

SMEX/WIRE was launched in March of 1999. Data received for the first six months of operation of the concentrator module has shown the expected level of performance. These data (Figure 13) show a small degradation of current that is expected from initial mirror contamination from spacecraft and solar panel outgassing products. Temperature data obtained from the LCP module indicates a backside temperature of 75C, which is consistent with the thermal analysis considering the low earth load in sun synchronous orbit.

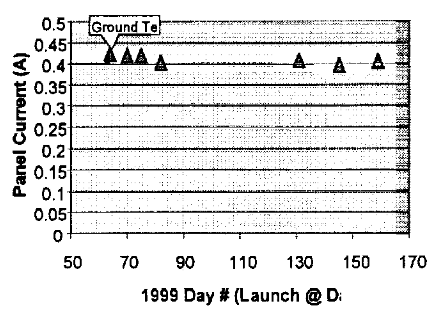

Figure 13. Space Flight Data from SMEX/WIRE Experiment

Conclusions

A concentrator panel has been designed and demonstrated that has equivalent properties to a planar panel, and is technology transparent in application. Since the design provides a plug-in replacement for a rigid solar panel, a flight experiment was easily implemented on the SMEX•LITE solar array, which uses modular rigid panels. Design, analysis and ground testing of a concentrator module for SMEX•LITE showed equivalent performance to the existing planar modules using the same type of cell. The flight testing of the LCP design on SMEX/WIRE has verified the predicted performance and shown the ability to maintain performance in the space environment.

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